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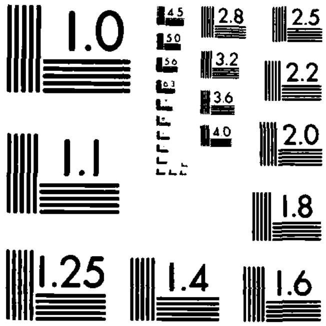

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Laboratory Observations of Ion-Cyclotron Waves Associated with a Double Layer in an Inhomogeneous Magnetic Field

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ABSTRACT

Observations of coherent electrostatic ion-cyclotron (EIC) waves associated with a strong, magnetized double layer are presented. The double layers are produced by applying a positive potential to an electrode located in a diverging, solenoidal magnetic field region of a weakly ionized argon plasma. Ionization within the electrode sheath is essential to the formation of these double layers. The resulting V-shaped potential structures have extended parallel, oblique and perpendicular electric field components. The frequency of the ion-cyclotron instability is dependent upon the position of the magnetic field-aligned potential structure. The propagation properties of the EIC waves are presented, and a discussion is given of the possible excitation mechanisms.

I. INTRODUCTION

Recently, there has been much interest in plasma potential structures called double layers, particularly in regard to the presence of parallel electric fields in the auroral region [see, e.g., Shawhan et al., 1978]. The existence of double layers in the earth's ionosphere and magnetosphere has been inferred [Mozer et al., 1977] from satellite measurements of strong electric fields at ~ 1 R_E. Generally, these potential structures appear to have regions where the electric field is predominantly parallel or predominantly perpendicular to the magnetic field. The parallel electric fields may accelerate positive ions upward or electrons downward toward the earth, the latter giving rise to increased auroral activity.

While there have been direct satellite measurements of potential differences assumed to result from double layers, e.g., Mozer et al. [1977], their existence has also been inferred from the distribution functions of upstreaming ions and precipitating electrons [e.g., Kan and Lee, 1981]. In these regions (~ 1 R_E) there have also been observations of coherent electrostatic ion-cyclotron waves (EIC) with frequencies near the fundamental and first few harmonics of the H^+ ion-cyclotron frequency [Mozer et al., 1977; Kintner et al., 1978].

The first definitive observations of magnetic field-aligned electric field structures in the auroral plasma (6000 - 8000 km) have been reported by Temerin et al. [1982]. These double layers differ from the previously reported electric field structures [Mozer et al., 1977] in that (1) the electric field amplitudes were much smaller, (2) the duration is shorter, and (3) they were predominately field aligned rather than perpendicular. The perpendicular components, however, do have spectral components indicative of electrostatic ion-cyclotron waves. Quite recently, Kellogg et al. [1984] have reported observations of double-layer-like structures in the auroral regions at much lower altitudes (585 km). About two-thirds of the observed transient electric structures showed frequency components very close to the proton-cyclotron frequency.

Since the initial observations there has been much discussion concerning the free-energy sources necessary to drive the EIC waves. Kintner et al. [1979] considered the possibility that either an electron drift or upstreaming ions (ion beams) were the source of free energy for the EIC waves observed from S3-3 satellite data. In a statistical study of the S3-3 data, Cattell [1981] concluded that an unambiguous identification of the free-energy source for the waves observed by Kintner et al. [1979] was not possible, and the waves could be driven by a combination of ion beams and electron drifts (field-aligned currents). In subsequent work Kaufmann and Kintner [1982] concluded that: "The simultaneous appearance and disappearance

of ion beams and waves first suggested a cause and effect relationship." This view is supported by a recent theoretical and numerical analysis of Okuda and Nishikawa [1984]. However, Bergmann's [1984] results indicate that the relative importance of the two processes is sensitive to the temperature regime, and that in the regime, $T_e \sim T_i$, the current-driven ion-cyclotron instability, modified by the presence of an ion beam appears to be the most likely mechanism for explaining the S3-3 wave data. In the 150 km - 300 km diffuse auroral region, Bering [1984] observed EIC waves which appear to be due to a field-aligned electron beam, since in this region the parallel current density corresponded to a drift velocity far below threshold for EIC wave generation. Laboratory studies of ion-beam excitation of ion-cyclotron waves have been carried out by Böhmer et al. [1976] and Yamada et al. [1977].

It has also been suggested that electrostatic ion-cyclotron waves may be responsible for the production of ion conics [Sharp, 1977], energetic (keV) H^+ and O^+ ions having pitch-angle distributions peaked at an angle to the magnetic field. Ions may be heated in the direction perpendicular to the magnetic field (transverse acceleration) [Ungstrup et al., 1979] in the presence of ion-cyclotron waves, and subsequently flow upward under the magnetic mirror force producing ion beams or conics. These escaping particles are considered an important terrestrial source of energetic ion distributions in the magnetosphere. Borovsky [1984] has performed numerical simulations

which suggest that ion-conic distributions may also result from a direct interaction of ambient ions with oblique double layers.

Laboratory double layers have been generated in a magnetic field in various ways: by applying a positive voltage between two plasma sources [e.g., Hatakeyama et al., 1983], by applying a voltage to an anode electrode in a plasma [Torvén and Andersson, 1979], or by injecting an ion beam [Stenzel et al., 1981] or an electron beam [Jovanović et al., 1982] into a plasma. Observations of low-frequency fluctuations associated with the double layers usually are limited to fluctuations of the position of the double layer itself [Torvén and Lindberg, 1980]. Sato [1982] was the first to report observations of ion-cyclotron fluctuations associated with double layers. He suggested that the two-dimensional double layer potential structure was crucial to the excitation of ion-cyclotron waves. Jovanović et al. [1982] produced a three-dimensional double layer by injecting a 30 eV electron beam into a fully ionized cesium plasma, but no oscillations in the ion-cylotron frequency range were observed.

In the present paper we report our investigations of the properties of EIC waves associated with a strong ($e\phi/kT_e \approx 5 - 15$), three-dimensional, magnetized double layer. The double layers are produced in the diverging magnetic field region of a cylindrical argon discharge. Our motivation is the need for a better understanding of the relationships between the generation of double layers and the excitation and propagation of EIC waves in an inhomogeneous magnetic

field. Our preliminary observations have been previously reported [Merlino et al., 1984], as well as similar observations by Nakamura et al. [1984].

In Section II we describe the experimental apparatus used and summarize the properties of the double layers which are necessary for an understanding of the behavior of the ion-cyclotron waves. Our observations of the ion-cyclotron waves are presented in Section III. A discussion and summary of these results is given in Section IV.

II. EXPERIMENTAL SET-UP AND PROPERTIES OF DOUBLE LAYERS

The experiment was performed in a cylindrical argon plasma discharge device, shown schematically in Figure 1(a). The discharge is generated between a directly heated conical spiral tantalum cathode (7 cm diam) and a grounded anode mesh. More details of the plasma source may be found elsewhere [Cartier and Merlino, 1984]. The solenoidal magnetic field diverges into a large end chamber with an axial dependence shown in Figure 1(b). Typical operating parameters were: discharge voltage ~ 60 V, argon pressure 10^{-4} - 10^{-3} Torr, $n_e \sim 10^{10}$ cm^{-3}, $T_e \sim 2$ eV, $T_i \sim 0.2$ eV. Plasma density and electron temperature were measured using Langmuir probes. The floating potential of an emissive probe was used to measure the plasma space potential. The full emissive probe characteristics were taken to check that the floating potential closely approximates the space potential. Measurements of the double layer properties were made using extremely small probes (probe shafts typically 0.2 mm diameter and disk diameter of 0.8 mm) to minimize perturbation to the double layer.

Double layer potential structures were generated in the device of Figure 1 by applying a positive voltage to the anode plate (diameter 20.5 cm) located in the diverging magnetic field region of the solenoid. As the anode plate voltage, V_p, was increased from zero,

initially a sheath was formed close to the anode plate. When V_p was increased to a value approximately equal to the argon ionization potential ($\approx$ 16 V) above the space potential, the sheath was transformed into a strong, bell-shaped double layer [see insert in Figure 1(a)]. The evolution of an unstable plasma sheath into a double layer has been described earlier [Torvén and Andersson, 1979], and occurs when an additional plasma source, due to ionization within the sheath, is present. At neutral pressures $\gtrsim 10^{-3}$ Torr, the onset of the double layer is accompanied by the appearance of a bluish cone (or bell)-shaped visible light emission structure (see Plate 1) due to excitation of the neutral argon atoms by electrons which have been accelerated through the double layer. The boundary of the light-emitting region appears to be slightly inside of (i.e., on the high-potential side) the potential jump. The visual property of the double layers enables us to document the perturbing effects of the Langmuir probes; a situation which is minimized by using miniature probes. The position of the tip of the cone, relative to the anode plate, increases as the plate voltage is increased. Visually, as V_p was increased, the entire light-emitting structure increased in length. This effect is shown quantitatively in Figure 2, where the axial potential profiles, at $r = 0$, are plotted for V_p between 40 and 60 V. Over this range of applied voltages the double layer potential jump, $\Delta\phi$, increases linearly from about 16 V to 30 V. These double layer potentials correspond approximately to $e\Delta\phi/kT_e \approx 5 - 15$. Over the

range of plate voltages used the argon ionization cross section is an increasing function of $\Delta\phi$, consequently as V_p is increased more (free) ions and (trapped) electrons are produced, and the double layer structure expands axially since the magnetic field prevents radial motion. However, radial ion losses and the presence of an axial density gradient (n increasing away from the anode plate) may be factors in determining the equilibrium position of the double layer.

Contours of constant potential showing the V-shaped double layer structure are shown in Figure 3(a). The shape of these potential contours, as well as the light emission structure, appear to follow the diverging magnetic field lines. These double layer's are topologically similar to those produced by Stenzel et al. [1981] by ion-beam injection, although our experiments were carried out at higher magnetic field strengths. The width of the potential jump, ΔL, for the parallel, oblique, and perpendicular electric fields (relative to B) are $\Delta L_{\parallel} \gtrsim \Delta L_{obl} > \Delta L_{\perp} \gtrsim \rho_i$, where ρ_i is the ion gyroradius. The The double layer width, ΔL, decreases with increasing pressure, scaling approximately with the Debye length, λ_D, and we find $\Delta L_{\parallel} \approx (10 - 100)\lambda_D$.

The qualitative features of the electron velocity distribution in the presence of the double layer were investigated using a double-sided Langmuir probe capable of distinguishing the direction of the electron velocity along the z axis. A well-defined electron beam of energy corresponding roughly to $e\Delta\phi$ was observed on the high-potential

side of the double layer, but the beam thermalized by about 15 cm from the double layer with a resulting electron temperature $T_e \approx 10$ eV. Although the mean-free path for ionization, $\ell_{ionz} \sim 2$ m for $p \sim 10^{-3}$ Torr, and $e\Delta\phi \simeq 20$ eV, a sufficient number of ions are created within the high-potential side of the double layer so that the condition $n_e \simeq n_i$ is satisfied [Torvén and Andersson, 1979]. Electrons undergoing ionizing collisions will loose ~ 16 eV and thus become trapped in the high-potential region. Elastic collisions may also be important in beam thermalization since the mean-free path for electron-neutral collisions, $\ell_{en} \sim 5 - 10$ cm. Evidence of a beam-plasma instability was also observed, which could also be a contributing factor in producing the trapped electron species. A more detailed presentation of the properties of the double layer will be the subject of another paper.

III. OBSERVATIONS OF ION-CYCLOTRON WAVES ASSOCIATED WITH THE DOUBLE LAYERS

Coherent low-frequency oscillations associated with the double layer were observed in the spectra of the Langmuir probe electron saturation current and space potential, and in the spectrum of anode plate current oscillations. The spectral peaks were near the harmonics of the local ion-cyclotron frequency corresponding to the position of the tip of the double layer. When the position of the double layer was moved by varying the plate voltage (as in Figure 2), the observed frequencies shifted as shown in Figure 4(a). For this case the Langmuir probe was at a fixed position on the high-potential side and the double layer position varied by changing the plate voltage, V_p. The observation that the frequencies did not depend on probe position was verified by keeping the double layer at a fixed position (i.e., keeping V_p fixed) and moving the probe along the axis, as shown in Figure 4(b). These observations are similar to those of Hatakeyama et al. [1980] in which the frequency of the ion-cyclotron instability, excited in a magnetic mirror geometry, was found to depend on the local value of B near the position of the current drawing electrode. In our case, the current-drawing electrode (anode plate) is fixed and the potential structure was moved in the inhomogeneous magnetic field

region. At a fixed anode plate voltage, the wave frequency was constant along the axis. For reference purposes we show in Figure 4(a) the ion-cyclotron frequencies corresponding to high- and low-potential regions on either side of the potential jump. In Figure 4(b) the horizontal line is the value of f_{ci} at the position where the potential has changed by half of its maximum value, $\Delta\phi/2$; whereas the dashed line is the local f_{ci} at the probe.

The propagation properties of the ion-cyclotron waves were studied by measuring the amplitude and phase of waveforms of either the floating potential or electron saturation current of a radially movable Langmuir probe. For this purpose the phase of the probe oscillations was compared, on a dual-beam oscilloscope, with the phase of the anode current oscillations. The waves propagate predominantly perpendicular to $\underline{B}$ with no detectable azimuthal phase shift. The series of plots shown in Figure 5 summarizes the plasma and wave properties for a double layer located at $z \cong 30$ cm and for the general conditions of Figure 3. In this series of plots radial profiles of plasma density, space potential, EIC wave amplitude, and wave phase are shown, at axial positions on the low-potential side of the double layer (Upstream) and high-potential side (Downstream).

Downstream of the double layer, the oscillation has the signature of a standing wave in the radial direction. The amplitude is maximum on axis, with nodes at the radial positions corresponding approximately to the largest radial electric field. Smaller amplitude

lobes appear on either side of the nodes, with approximately constant phase. There is approximately a 180° phase difference between the center and nodal point over a distance of ~ 1.5 cm, implying radially inward propagation over a distance comparable to the width of the potential drop perpendicular to $\underline{B}$. Upstream of the double layer, the wave amplitude is again largest in the center, with a slightly lower amplitude peak on either side. At this position the oscillation seems to be a mixure of standing and travelling waves since there are no nodal points (zero amplitude) and only an ~ 45° phase shift. This phase change occurs over a distance of ~ 2 cm, with the waves propagating both inward (toward the axis) and outward from the position of minimum amplitude.

In an attempt to understand the complex propagation properties of the waves, we thought it useful to determine the radial distribution of the anode plate current. To accomplish this the electron current drawn to a small Langmuir probe located a few centimeters in front of the plate and biased at the plate potential was measured vs r. This current density profile was not radially uniform and was about a factor of 10 higher in the outer regions just inside the radial density gradient, as compared to that on axis. From these measurements and the measurements of the density profile, the radial profile of electron drift velocity could be determined from $v_D = j_e/n_e e$, where j_e is the measured electron current density. This result was shown in Figure 3(b). The observed current profile seems

to be consistent with the downstream propagation characteristics which showed inward propagating waves. Upstream, predominantly outward-going waves were observed which could be associated with the radial compression of the current channel in the high B-field region.

IV. DISCUSSION AND SUMMARY

We have presented observations of oscillations due to an electrostatic ion-cyclotron instability in the presence of a strong, three-dimensional double layer. The frequency of the instability is dependent on the position of the tip of the double layer, which is movable in regions of inhomogeneous magnetic fields. For ion-cyclotron waves excited by drawing an electron current to a biased electrode within the plasma column, the dependence of the ion-cyclotron wave frequency on the position of the electrode in an inhomogeneous magnetic field has been seen previously [see Hatakeyama et al., 1980; Krumm and Alport, 1984; Cartier et al., 1985]. In the present experiment the electrode (anode plate) is fixed while the position of the potential structure itself is movable.

In attempting to understand the excitation and propagation properties of the ion-cyclotron waves, we need to consider the role of inhomogeneities in the magnetic field, plasma density, space potential, and electron current density. For a uniform plasma carrying a (uniform) current in a homogeneous magnetic field, the theoretical results of Kindel and Kennel [1971] may be considered in the limit of large T_e/T_i, applicable to our discharge plasma. Under these conditions for an argon plasma, we would expect the electrostatic

ion-cyclotron waves to be excited for a critical drift $v_D \gtrsim 8\ v_i$, where v_i is the ion-thermal velocity, and at a frequency $f \approx 3/2\ f_{ci}$, and wave numbers $K_\perp/K_\parallel \approx 2 - 3$. With the double layer present there are three potential free-energy sources to drive the EIC waves: the electron drift associated with the field-aligned current, ions accelerated through the double layer toward the upstream side, and electrons accelerted downstream. At the relatively high neutral pressures used in this experiment to generate the double layers, the mean-free path for $A^+ - A$ charge exchange collisions is $\approx 5 - 10$ cm so that an ion beam formed by acceleration through the double layer potential (i.e., the free-ion species) would be rapidly attenuated. Thus for our particular parameters, an ion-beam driven mechanism seems unlikely.

In connection with the possible excitation of the ion-cyclotron waves by electrons accelerated by the double layer, the following points can be made. (1) The parallel phase velocity, $\omega_{ci}/k_\parallel$, corresponding to the electron beam velocity ($\sim 2 \times 10^8$ cm/s) for a typical double layer ($e\Delta\phi \approx 20 - 30$ eV) results in a parallel wavelength much longer than the length of the device. In the experiment of Jovanović et al. [1982], no oscillations in the ion-cyclotron frequency range were observed when a beam of similar energy was injected into a plasma. However, in their case the electron beam diameter was somewhat less than the ion-gyroradius, so that the instability may have been quenched [Bakshi et al., 1983; Cartier et al., 1985]. (2) If the

EIC instability was excited by electrons accelerated in the double layer potential, we would have expected to see the waves limited to the high-potential region, which apparently was not the case.

We are thus led to the tentative conclusion, that since neither an ion-beam or electron-beam excitation process appears likely, the ion-cyclotron waves must be excited by the electron drift associated with the field-aligned current. This mechanism is similar to the usual case of excitation in a uniform plasma, by biasing a small electrode. Of course, the local theory of this process [see, e.g., Drummond and Rosenbluth, 1962; Kindel and Kennel, 1971] does not account for some of the properties of the waves produced under the inhomogeneous conditions of the experiments, in particular the dependence of wave frequency on position of the electrode or, in our case, the position of the tip of the double layer. Some of the nonlocal effects, e.g., the finite current channel widths, require a nonlocal theory [see, e.g., Ganguli and Bakshi, 1982; Bakshi et al., 1983]. However, the excitation properties can be discussed within the general framework of the current-driven mechanism. In this connection it is apparent that the presence of the double layer significantly alters the plasma characteristics, and in particular gives rise to a depression of the density on axis [see Figure 5(a)]. This density depression would presumably introduce a z dependence in the drift velocity, v_D, increasing toward the double layer, which might explain

the local excitation of the ion-cyclotron waves at the position corresponding to $v_D > v_{D,critical}$.

If the excitation of the ion-cyclotron waves occurs near the "tip" of the double layer, one would expect propagation only within the high-potential side of the double layer, for a current-driven mechanism; and only upstream of the "tip" if the accelerated ions are responsible. However, the ion-cyclotron waves apparently propagate both upstream and downstream, although as we move away from the double layer (to regions of higher B), the wave amplitudes decay faster with r. This might be due to the fact that upstream $\omega < \omega_{ci}$, which according to the dispersion relation $\omega^2 = \omega_{ci}^2 + k_\perp^2 C_s^2$ (derived for a uniform plasma) would not permit radially propagating waves. It is, of course, possible that no single free-energy source is responsible for the observed EIC instability.

Recently, a new mechanism for ion-cyclotron wave excitation has been proposed by Ganguli et al. [1985], based on the presence of a nonuniform electric field perpendicular to a uniform magnetic field, in the absence of any field-aligned current. They show that the instability exists for $v_E/v_i \sim 3$, where $v_E = E_\perp/B$. For our experimental conditions, when the double layers are present, $E_\perp \approx$ 20 V/2 cm = 10 V/cm, B ~ 500 G - 1000 G, and $v_E \sim 1 - 2 \times 10^6$ cm/s, well above the minimum necessary for the onset of this instability. This new mechanism, based on the presence of $E_\perp$, would be consistent with the observation that the waves appear to propagate inward (on the

downstream side) from a radial position corresponding roughly to the region of the perpendicular potential jump. However, the drift velocity of the field-aligned current does appear to be largest in this region so that either mechanism may be possible. Of course, in any case, the dependence of the wave frequency on the position of the "tip" of the potential structure remains to be explained.

In summary, we have presented evidence for electrostatic ion-cyclotron waves associated with a strong, three-dimensional double layer in a diverging magnetic field geometry. The wave frequency depends upon the position of the magnetic field-aligned potential structure of the double layer (largest $E_\parallel$). For our particular set of experimental conditions, the most likely excitation process is the electron drift associated with the field-aligned current, although the mechanism due to the presence of a nonuniform $E_\perp$ [Ganguli et al., 1985] is another candidate. Further consideration of this $E_\perp$ mechanism should be made when more details become available. Such a mechanism may also be important in the auroral context where ion-cyclotron waves have been reported in connection with stationary potential structures perpendicular to $\underline{B}$ [Mozer et al., 1977; Temerin et al., 1982].

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PLATE CAPTION

Plate 1. Color photograph of luminous plasma potential structure. The plasma discharge source is to the right in this photograph [see Figure 1(a)]. The boundary of the light-emitting region follows the diverging magnetic field lines and lies slightly to the inside of the potential jump. For this photograph the neutral argon pressure was $\sim 3 \times 10^{-3}$ Torr.

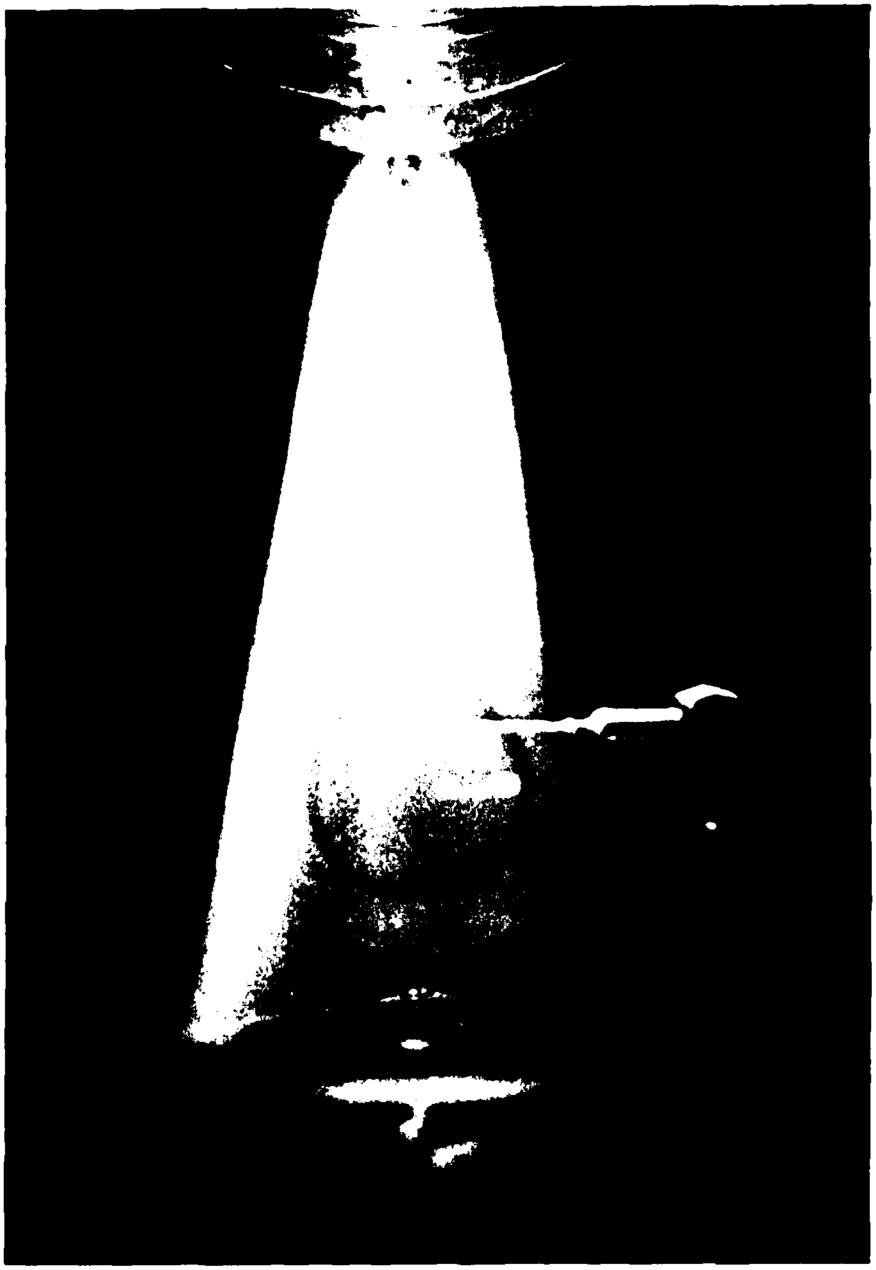

Plate 1

FIGURE CAPTIONS

Fig. 1. Schematic of the experimental set-up. (a) Plasma discharge source and anode plate which when biased produces plasma potential structures. Magnet coils (not shown) occupy the region between $z \cong 40$ cm and $z \cong 130$ cm. Insert shows schematic of the conical double layer structure. (b) Axial magnetic field vs z in the end region of the device. $z = 0$ corresponds to the plate position and the position $z = 62$ cm corresponds to the transition between the large end chamber and main chamber.

Fig. 2. Axial profile of the plasma space potential for various anode plate voltages with $p = 1 \times 10^{-3}$ Torr, and magnetic field coil current $I_c = 500$ A. The magnetic field strengths are shown for $z = 10$, 20, and 30 cm.

Fig. 3(a). Two-dimensional (r,z) mapping of equipotential contours. Note scale is (1:4). Numerical values of potential (in volts) are shown for various contours with the inner contours given in 5-volt intervals. (b) Drift velocity (arbitrary units) of electrons collected by the anode plate at an axial position approximately 1 cm in front of the plate.

Fig. 4. Ion-cyclotron wave frequency. (a) Axial variation of oscillation frequency observed on a probe at a fixed position within the high-potential side vs plate voltage. The solid curves show variation of f_{ci} at two positions on the low- and high-potential side as indicated in the insert. (b) Oscillation frequency observed on a probe moved to various axial positions for a double layer at a fixed position (i.e., V_p fixed). The local f_{ci} at the probe and double layer are also shown.

Fig. 5. Radial profiles of (a) plasma density, (b) space potential, (c) wave amplitude, and (d) wave phase for two axial positions on the low-potential side (upstream) and within the high-potential side (downstream) of the double layer. The density, space potential, and wave amplitude are given in arbitrary units.

A-G84-381

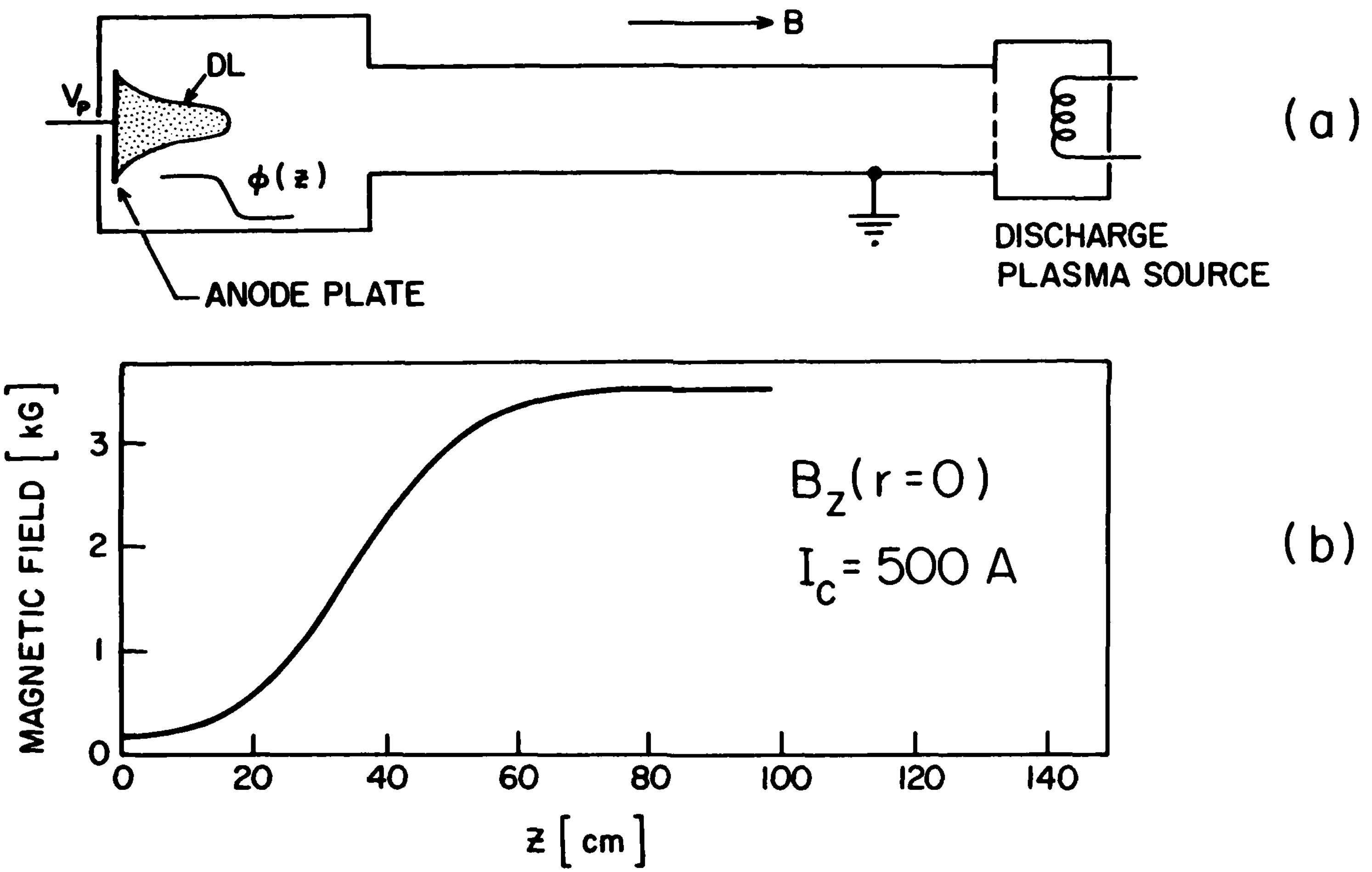

Figure 1

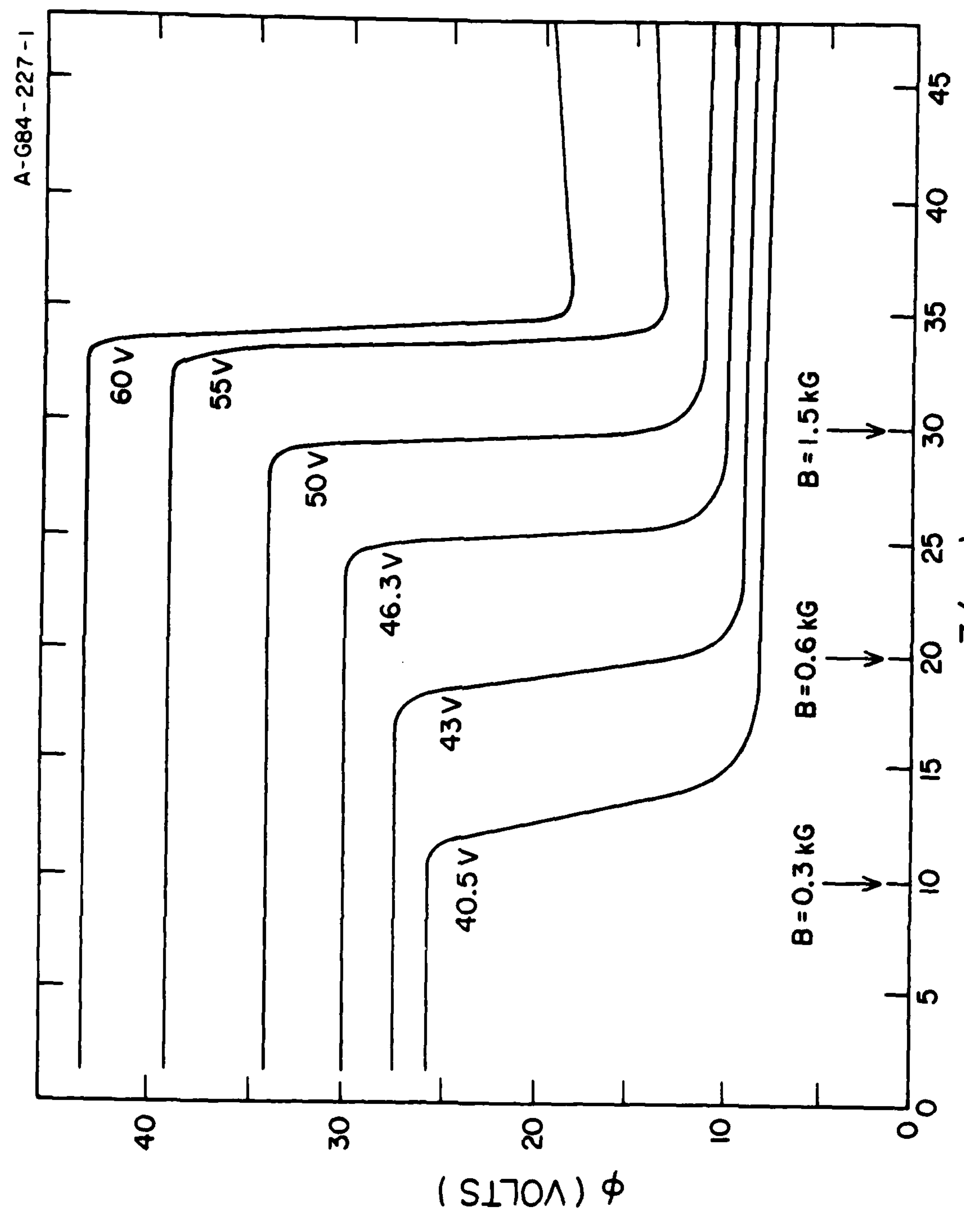
A-G84-227-1
60 V
55V
50V
46.3 V
43V
40.5V
B=0.3 kG
B=0.6 kG
B=1.5 kG
Z (cm)
ϕ (VOLTS)
0
5
10
15
20
25
30
35
40
45
0
10
20
30
40

Figure 2

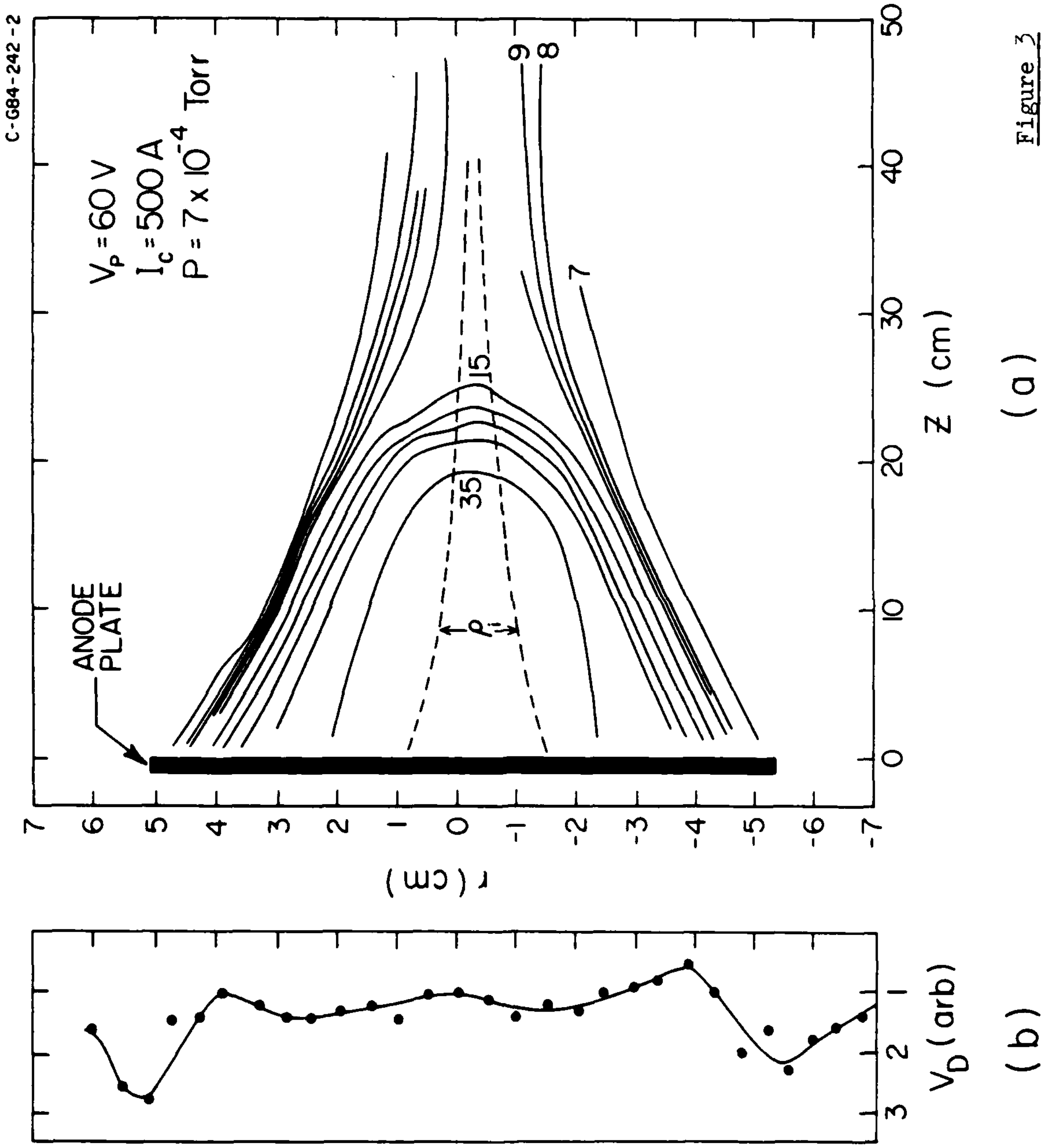
C-G84-242-2
$V_p = 60$ V
$I_c = 500$ A
$P = 7 \times 10^{-4}$ Torr
ANODE PLATE
9
8
7
15
35
ρ
Z (cm)
r (cm)
V_D (arb)
(a)
(b)

Figure 3

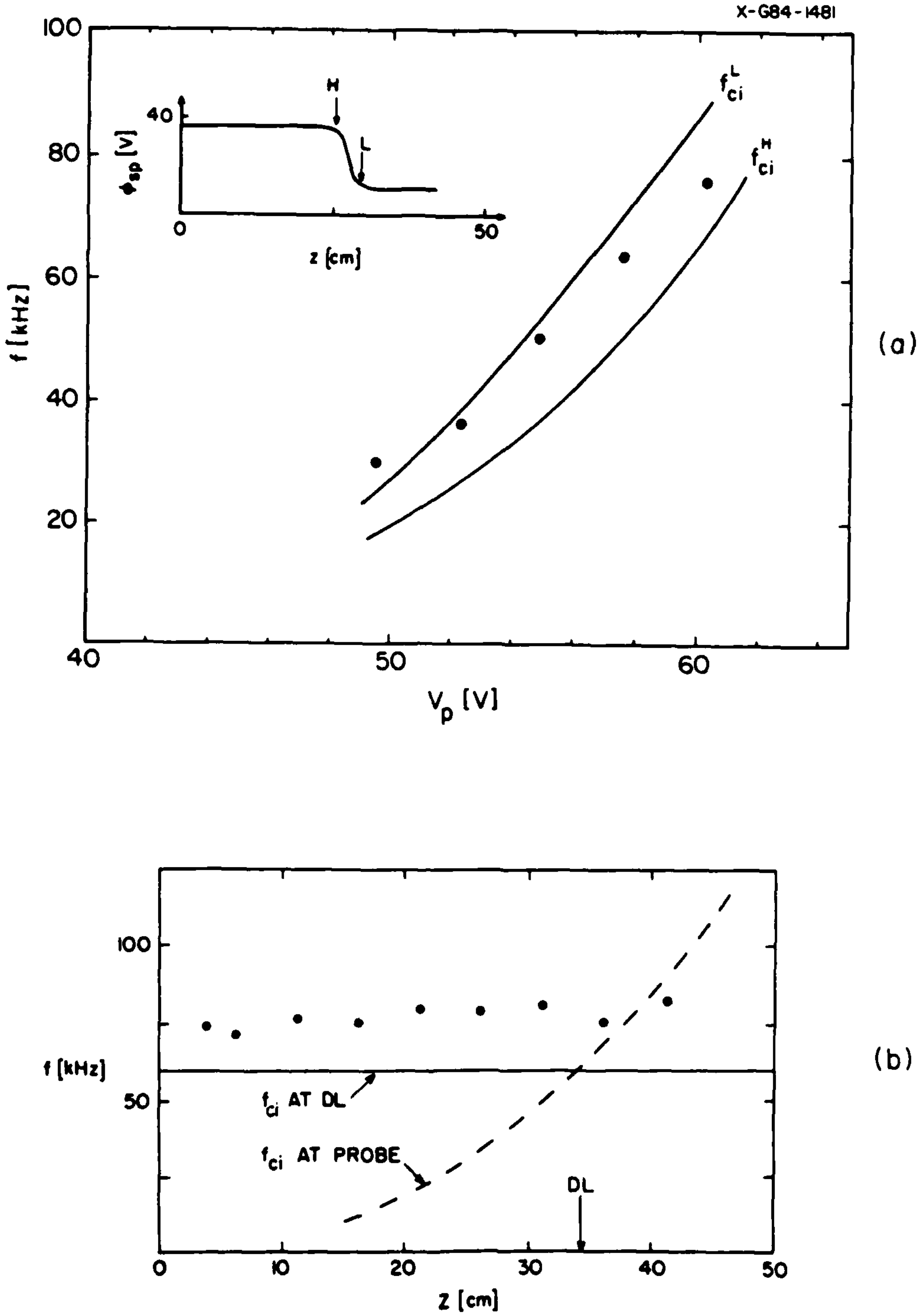
X-G84-1481
100
80
60
40
20
f [kHz]
40
50
60
V_p [V]
f_{ci}^L
f_{ci}^H
40
ϕ_{sp} [V]
H
L
0
50
z [cm]
(a)
100
f [kHz]
50
f_{ci} AT DL
f_{ci} AT PROBE
DL
0
10
20
30
40
50
Z [cm]
(b)

Figure 4

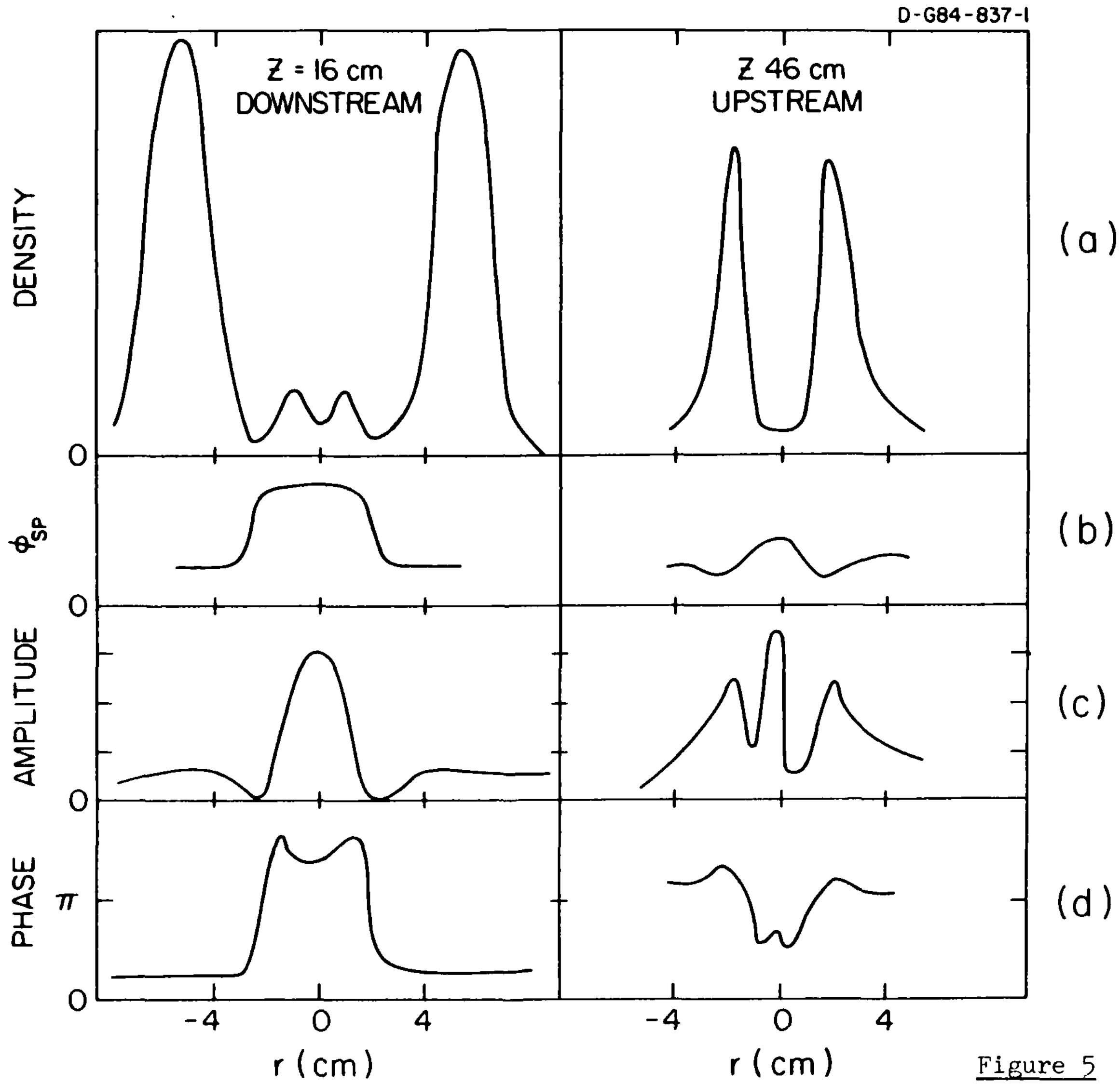
D-G84-837-1
Z = 16 cm
DOWNSTREAM
Z 46 cm
UPSTREAM
DENSITY
ϕ_{sp}
AMPLITUDE
PHASE
π
0
-4
0
4
r (cm)
(a)
(b)
(c)
(d)

Figure 5

END

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